THz Communications – A Candidate for a 6G Radio?

[Invited]

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***Abstract*— W the first 5G networks are about to be launched, the discussion within the scientific community about the next generation Beyond 5G or 6G has already kicked-off. One of the candidate technologies for a 6G radio access technology is THz communications, which uses spectrum mainly beyond 275 GHz enabling the use of channel bandwidths of several 10s of GHz. This contribution provides an overview on current state-of-the art of THz communications in research, standardization and regulation and discusses the challenges to make THz communications a promising candidate for a 6G radio.**

Keywords—THz Communications; 6G Radio; Standardization

I. Introduction

While the first 5G networks are about to be launched, the discussion within the scientific community about the next generation beyond 5G (B5G) or 6G has already kicked-off. Although for single 5G radio access links data rates of several Gbps are foreseen, much higher data rates will be required for the aggregated links in the backhaul. For example, the NGMN 5G White Paper from 2015 predicts already traffic densities of several Tbps/km^2 [1] in ultra-dense networks. This will require backhaul/fornthaul links of 100 Gbps already in the context of 5G. The recently published 6G White Paper [2] forecasts peak data rates of 100 Gbps to 1 Tbps. One of the candidate technologies capable to achieve such data rates for 5G backhaul/fronthaul links and in 6G radio access technology is THz communications. THz communications uses spectrum mainly beyond 275 GHz enabling the use of channel bandwidths of several 10s of GHz. Fundamental research on THz communications has started already in the early 2000s [3,4] and first demonstrators showing the capability of wireless 100 Gbps/s appeared a few years ago, see e. g. [5], [6]. For a limited number of use cases and applications [7] technology has been already mature enough to develop IEEE Std. 802.15.3d-2017 [8], which has become the world's first 300 GHz wireless standard. Also the process for a proper regulatory framework has been triggered already, see e. g. [9,10,11].

Despite these early demonstrations of the feasibility of THz communications to provide the demand for ultra-high data rates, still big challenges have to be met to make THz communications operational in a broader range of applications. Worldwide large research programs dealing with THz communications have been initiated. For example within the European Horizon 2020 framework programme a cluster of seven projects [12] dealing with different aspects and applications of B5G networks has been created and in Finland a 6G flagship initiative [2] has been funded. This contribution provides an overview on current state-of-the art of THz communications in research, standardization and regulation and discusses the challenges to make THz communications a promising candidate for a 6G radio. The remaining part of the paper is structured as follows: A selection of obvious potential application scenarios is described in section II followed by an overview of open challenges in section III. A brief description of the current status in standardisation and regulation is provided in section IV. Conclusions are drawn in section V.

II. Potential Application Scenarios

In [2] augmented, virtual and mixed reality technologies are mentioned as one of the drivers for the demand of ultra-high data rates.

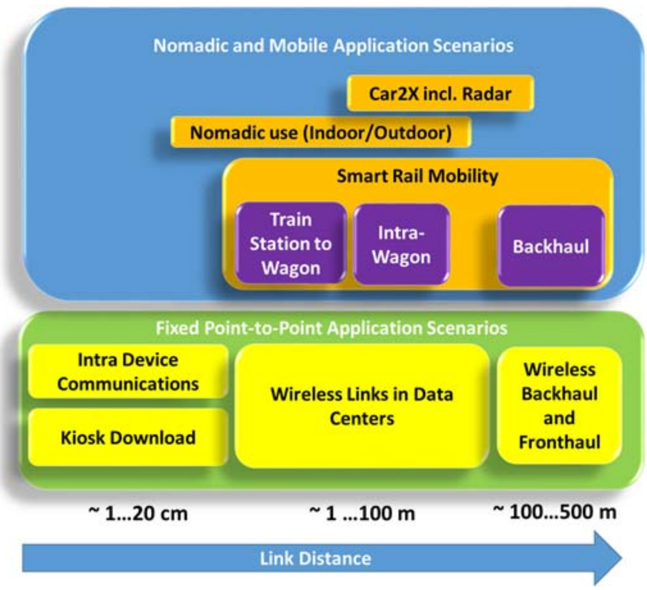

Figure 1: Categorization of application scenarios into nomadic/mobile applications and fixed point-to-point applications including the indication of the typical link distance.

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Such applications influence a multitude of application scenarios. A more technical categorization of use cases of such application scenarios is provided in [7,13] targeting also other applications from which the categorization described in the following and depicted in Figure 1 has been evolved. The specific application scenarios can be grouped into *Fixed Point-to-Point Applications*, where the location of both ends of the radio links are fixed and a-priori known and *Nomadic and Mobile Applications*, where the location of at least one radio terminal of each link is not known a-priori and/or may move.

A. Fixed Point-to-Point Applications

Applications in this category do not require complex procedures for device discovery, beam steering and beam tracking. It can be assumed that the locations of the antennas are known and hence the use of antennas with the required gain and properly aligned during installation is sufficient. For these four applications, technology has been considered mature enough to develop IEEE Std. 802.15.3d-2017 addressing four application scenarios:

- *Intra-device communication:* For links within devices, e. g. an ultra-high-definition camera, data rates of 100 Gbit/s might be easily exceeded [7]. For example an 8K resolution at 120 Hz and 36 bits per pixel requires 143 Gbit/s of gross data rate [14]. In order to provide these data rates wireless THz communications is a promising candidate, which has been subject to past or ongoing research projects [15,16,17,18].
- *Kiosk Downloading* provides the possibility of downloads of large amount of digital information to mobile terminals over a short distance and has been investigated e. g, in [19]. An exemplary scenario is described in [7] for an ultra-fast file downloading of a video at the toll gate of a train station.
- *Wireless Links in Data Centers*: The network architecture and the associated links in data centers need to be frequently reconfigured in order to accommodate the frequently changing traffic profiles [20]. In a purely wire connected data center such a reconfiguration requires manual solutions, and is time-consuming and error-prone. For example, complementary wireless links, for example realized via top-of-the rack nodes, can introduce more flexibility and potential automation. To achieve the high data rate demands THz communication is promising option and the EU Horizon 2020 TERAPOD project ("Terahertz based Ultra-High Bandwith Wireless Access Networks") [21,22] is working towards a prototypical implementation of THz wireless links in a data center.
- *Backhaul/Fronthaul links:* In order to realize the data traffic densities of several Tbps/km^2 mentioned above, THz backhaul/fronthaul links are a possible solution, if fiber links are not available at every base station. The corresponding concepts are already developed in a couple of projects, for example, the EU-Japan project ThoR ("TeraHertz end-to-end wireless systems supporting ultra-high data Rate application") which is working towards a demonstrator of this application [23,24,25] based on the standard defined in [8].

B. Nomadic and Mobile Applications

Nomadic and mobile applications require intelligent antenna solutions enabling device discovery (for nomadic and mobile applications) and beam tracking (for mobile applications). Additionally the problem of dynamic human blockage [26] has to be mastered. The corresponding applications are briefly described in the following:

- *Nomadic applications (indoor/outdoor):* Possible applications, where ultra-high data rates may be required are access points for locations serving huge crowds with high traffic demand like in conference centers, exhibition halls or sports stadiums.
- *Smart Rail Mobility:* In [27] THz communication is described in the context of smart rail mobility. This application comprises a variety of different sub scenarios including (a) links between the train station and the wagons, where data is downloaded to the train in a similar way as in the kiosk downloading described above, (b) intra-wagon links providing passengers access to the in-train communication system and (c) backhaul links, which connect the train to the outside network.
- *Car-to-X-Communications and Radar:* First concepts to apply THz frequencies to car-to-X communications and radar are recently described in [28, 29] allowing both ultra-high data transmission and high resolution of the radar due exploiting the ultra-high bandwidths. In order to provide a validation and further insights for the scenarios introduced in [29] a first measurement campaign using a 300 GHz time domain channel sounder has been performed recently [30].

III. CHALLENGES

Technical challenges to make THz communication happen, can be observed in the whole chain of the communication system and will be roughly sketched in the following.

A. Propagation Channel

Apart for the high free space path loss observed at the THz frequency range a couple of phenomena, which can be neglected in the UHF range have to be considered. The most important phenomena in this context are atmospheric attenuation and the effect of surface roughness. Due to the small wave length of 1 mm and below very small structures, which can be considered flat at lower carrier frequencies become rough. This requires that all these effects are characterized by measurements and new models have to be developed. A selection of exemplary results and models can be found in [31,32,33].

B. Antennas

Especially, the above described nomadic and mobile applications are very demanding wrt antenna concepts. This

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includes both algorithms and procedures for device discovery, beam steering and beam tracking [34, 35] as well as the design of the required antenna arrays itself. On one hand the small wave lengths allow the design of compact antenna structures, which require relatively small space when it comes to the deployment. On the other hand the design of antenna arrays requires a spacing in the order of a half wave length for the single antenna elements in order to provide sufficient side lobe suppression. Such a tight spacing is challenging in terms of fabrication. A first proof-of-concept based on antenna arrays consisting of four horn antennas is presented in [36,37,38], which also demonstrates the limits of this concept wrt achievable side lobe suppression. Another approach based on planar structures is described in [39].

C. RF Frontend

For the realization of the RF front end both electronic approaches, e.g. [40,41,42,43], and photonic approaches, e.g. [44,45], can be found. The electronic approaches comprise III-V [40, 41] and silicon technologies [43] including first approaches towards CMOS [42]. One problem, which occurs at higher frequencies is phase noise, which limits the application of higher-order modulation schemes. To mitigate the phase noise problem combined photonic and electronic approaches have been recently proposed [46]. The generation of sufficient output power especially for the larger link distances at backhaul applications for example is another challenge, which is addressed by the development of travelling wave tube amplifiers, see e.g. [47].

D. Baseband Processing and Networking Interface

With ultra-high data rates the requirements for digital-to-analog and analog-to-digital conversion, the performance of forward error correction channel coding and interfacing to the network are demanding. Within the above mentioned B5G cluster [13] three projects are addressing aspects of these challenges. The EPIC project [48,49] is dedicated exclusively to channel coding and is investigating the coding families low-density parity check (LDPC) codes, turbo codes and polar codes especially wrt to efficient implementations. The Terranova project [50] has successfully demonstrated a concept of directly interfacing fiber optics with THz wireless. The concept followed by the ThoR project [51] targets an implementation, which is quasi-compliant with IEEE Std. 802.15.3d-2017 using chipsets from IEEE Std. 802.15.3e-2017 [52].

E. Metrology

The ultra-high frequencies in combination with ultra-high data rates brings also metrological challenges. The FOR 2863 Meteracom research unit [53], funded by Deutsche Forschungsgemeinschaft (DFG) in Germany addresses the grand challenge of metrology in THz communication measurements systematically, and in four distinct areas: (i) traceability to the International System of Units (SI), (ii) characterization of the measurement system itself, (iii) metrological characterization of the RF components and the propagation channel and (iv) measurements required for enabling the functionality of THz communications. Meteracom consists of nine sub projects, which are assigned to 4 projects each of them addresses one of the grand challenges, see Figure 2.

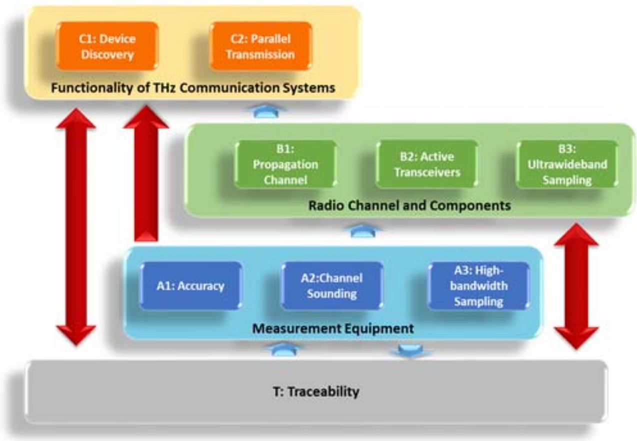

Figure 2: Meteracom project structure.

The central equipment used in Meteracom are a time domain channel sounder [54], which enables dynamic channel measurements at 300 GHz with a bandwidth of 8 GHz and a pure optical sampling system based on frequency-time coherence and an almost ideal sinc sequence generation [55].

IV. CURRENT STATUS OF STANDARDISATION AND REGULATION FOR THZ COMMUNICATIONS

In 2017, IEEE Std. 802.15.3d-2017 was approved on 28th September 2017 and published on 12th October 2018 as the worldwide first wireless communications standard operating at the 300 GHz frequency range [8]. The standard has defined two physical layer (PHY) modes, which comprise 7 modulation and three forward error correction (FEC) formats. The two PHY modes and the corresponding modulation and FEC schemes defined in the standard are displayed Figure 3. The modulation and coding schemes as well as large parts of the MAC layer have been inherited from [52].

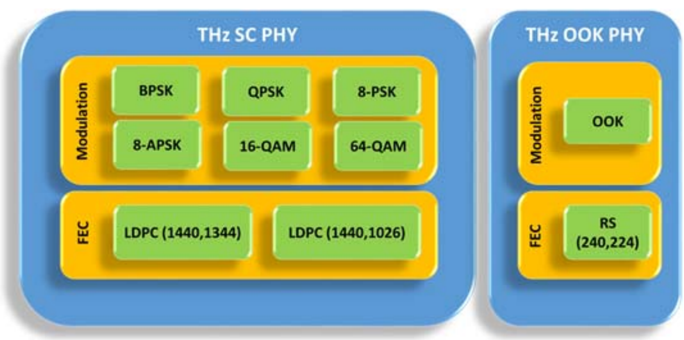

Figure 3: PHY modes, modulation and FEC schemes defined in IEEE Std. 802.15.3d-2017

The standard is defined in the frequency range 252-321 GHz with a flexible bandwidth allocation. 8 different channel bandwidths between 2.16 GHz and 69.12 GHz have been

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defined. The standard is limited to fixed point-to-point links and therefore targets the applications described in section II.A. Whereas the frequency band 252-275 GHz has already allocations for of Mobile Service (MS) and Fixed Service (FS), no allocation exists beyond 275 GHz [56]. In this frequency range only the footnote 5.565 exists, which protects passive services like Earth Exploration Satellite Service (EESS) and Radio Astronomy (RA) from harmful interference. In order to have globally harmonized regulations for the operation of THz communications in this part of the spectrum the identification of frequency bands for MS and FS between 275 GHz and 450 GHz has been investigated at the Word Radio Communications Conference (WRC) 2019, see e.g. [9,10,11].

V. Conclusions and Outlook

THz communications has been subject to research for more than 15 years. Although a first level maturity has been achieved already allowing impressive demonstrations and the development of a first standard, still numerous challenges have to be overcome. Large research initiatives are currently working on these challenges. This might bring THz communications to a level of maturity, where it will be well positioned to be selected as one radio access technology in future 6G wireless systems.

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